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Optical design for the DLP pocket projector using LED light source

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Abstract

The DLP [1] pocket projector can be classified into two parts according to design characteristic. One of them is illumination system. It composes of Red, Green and Blue LEDs. Each of them has a collimator to make lights illuminate dichroic filter collimated. By dichroic filters it combines three wavelengths lights together. The last part is the micro-lens array, condenser and TIR prism is used to illuminate DMD uniformly and reduce the size of illumination system. The other is imaging system. According to the standard of DMD; the angle of view, effective focal length, the relationship of imaging and object and imaging quality of the lens can be defined. By using optical simulation software, Code V and ZEMAX, the lens conform to the standards was well designed. Finally the tolerance of production was analysed. In this design, the average light efficiency of three wavelengths LED on DMD is 51.13%, and the average uniformity on DMD is 95.17%. About the screen, the average light efficiency is 44%, and the average uniformity is 87.3%.

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Keyword: DLP, LED, DMD, micro-lens array, uniformity

1. Introduction

In recent years, the improvements of projectors are not only in the resolution and color, but also in miniaturization and lightweight, especially when small and powerful light source being published. The projection display technology will turn into personalize. By using LED light source, DMD panel, micro-lens array and TIR prism we can reduce the size and weight with high efficiency, and high uniformity. It is an idea to make projection system popular.

2. Optical system

In this paper, the optical system can be classified into two parts according to design characteristic. One of them is illumination system; the other one is imaging system. As show in Fig. 1, our system was made up of LED light source, collimator lens, dichroic filters, micro lens array, mirrors, condenser, TIR prism, DMD, and projection lens.

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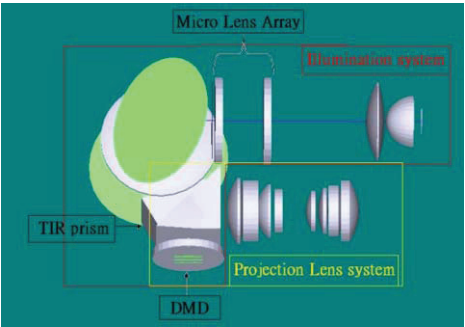


Fig. 1 System layout

3. Illumination system

3.1 LED specifications

In this design we choose “Phlatlight pt54 projection chip” [2] to be our light source. Because of it is bright enough and the size is small. By pulsing RGB LEDs at height frequency more than 60 Hz and synchronizing with the corresponding color that display on the DMD chip. A full color image is projecting. The shape of LEDs and the luminous intensity distribution curve are show as below. It has collimated angular intensity distribution for Green and Blue devices and Lambertian angular intensity distribution for Red devices. Over 1,300 white lumens at 8000K color temperature from a single RGB chipset under continuous operation.

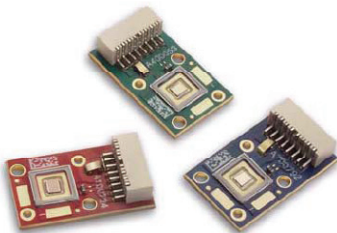


Fig. 2(a) Phlatlight pt54 RGB LED

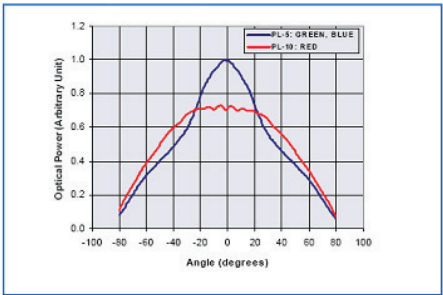


Fig. 2(b) Luminous intensity distribution curve of RGB LEDs

3.2 Design of collimator lens

Because there is no condenser with Phlatlight RGB LEDs, and the divergence angle is wide. So we have to design collimator lens for each LED to increase light efficiency and controlling the route of light. The size of our design is $30\text{ mm} \times 30\text{ mm} \times 22.2\text{ mm}$ and the intensity is confined in $\pm 10^\circ$. By using this condenser we can collect the lights in divergence angle at 60° .

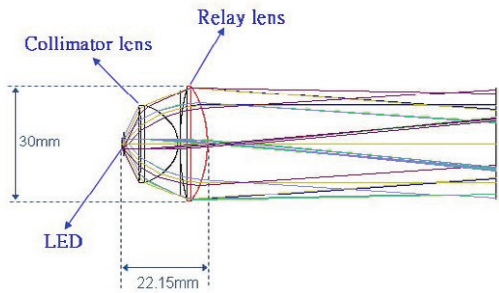


Fig. 3(a) Collimator lens layout

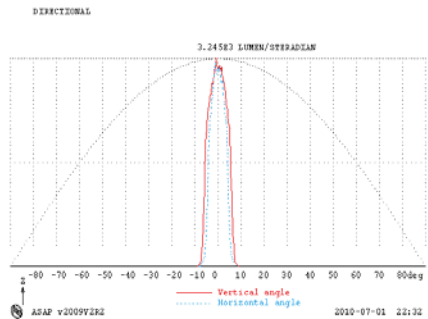


Fig. 3(b) The luminous intensity distribution curve after collimator lens

3.3 Dichroic filter

Because three different wavelength LEDs have to share the same route, we have to combine them together. By using two different dichroic filters with multilayer coating, it can make red or blue light reflection and green light transmittance to micro lens array as show in Fig. 4. Therefore the light source module becomes larger. The volume increased to $60\text{ mm} \times 78\text{ mm} \times 40\text{ mm}$ finally.

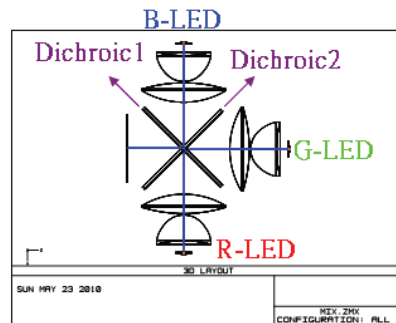


Fig. 4 The fabrication of dichroic filter

3.4 Micro lens array

To design micro lens array we need to calculate the area of it. We consider the lights have Lambertian characteristic. Therefore we can calculate the area of micro lens array by using this formula $A = \pi A_{\text{chip}}^2 \theta_{\text{half}}^2$, etendue [3] invariant at micro lens array to DMD. And we consider 20% overfill to avoid the boundary of lighting area. This makes it easier to get more uniformity on DMD. Then we got the area of micro lens array is 229.6 mm^2 . The design of micro lens array is show in Fig. 5.

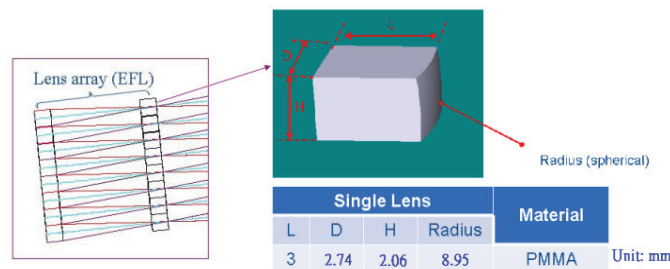


Fig. 5 The design of micro lens array

3.5 TIR prism

In this design we use TIR prism [4] as show in below to connect illumination system and imaging system. By changing the route of light, we can reduce the size of the optical system. About the design of TIR prism we set the angle of incidence at DMD is 26° to increase the contrast. By Snell's Law and geometrical relationships, we can decide the angle of prism 1. Finally, the size of our TIR prism is $31\text{ mm} \times 28\text{ mm} \times 25.25\text{ mm}$.

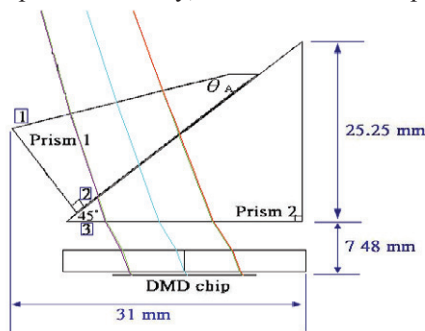


Fig. 6(a) The size of TIR prism

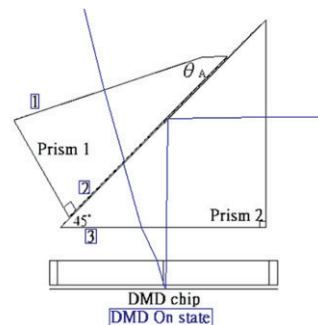


Fig. 6(b) The TIR prism layout with DMD On state

4. maging system

4.1 Fundamental specification

To design the imaging system, we have to set the fundamental specifications at first. According to the standards of DMD panel [5-7] and throw ratio, the fundamental specifications are decided as Table 1. By the fundamental specifications, we can star to design the projection lens in ZEMAX.

| Item | Parameter | Specification |
|------|------------------------|--------------------------------|
| 1. | DMD | 0.55" 4:3 |
| 2. | DMD Pixel size | 13.6 μm |
| 3. | Active area of DMD | 11.17 * 8.38 (mm) ² |
| 4. | Wavelength Range | 450 ~ 680 nm |
| 5. | Effective Focal Length | 14.2 mm |
| 6. | F/# | 2.4 |
| 7. | Field of view (FOV) | 65° |
| 8. | Total track | < 52 mm |
| 9. | Exit pupil position | 236 mm |

Table 1 Fundamental specifications

4.2 Project lens design

After optimized by ZEMAX, the project lens was well designed. The following is the layout and performances of this lens. About the MTF, at 37 lp/mm in all fields are over 60%. The optical distortion is 1.2%. The lateral color is less than 17 μm . And the relative illumination is 78%.

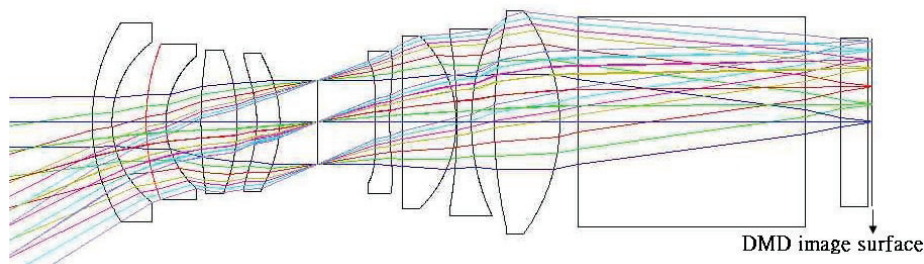


Fig. 7(a) The layout of project lens

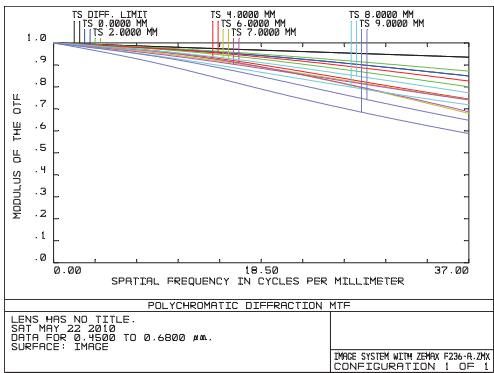


Fig. 7(b) MTF vs. fields

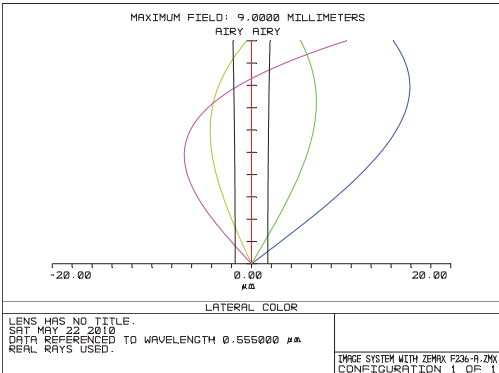


Fig. 7(c) Lateral color

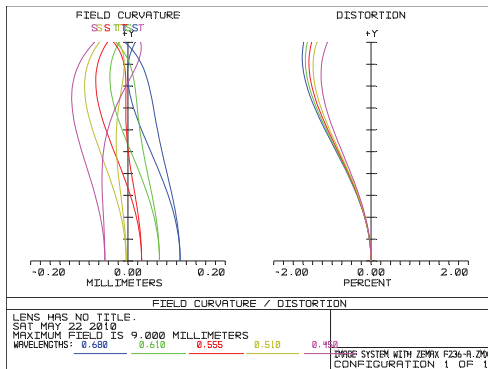


Fig. 7(d) Field curvature and distortion

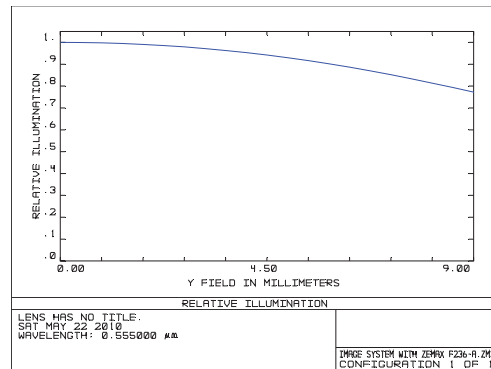


Fig. 7(e) Relative illumination

4.3 Tolerance analysis

There are inaccuracies in the production process, and it will make the performance not equal to expectations. Therefore we have to estimate the tolerance before production. By using Code V, we analyze the tolerance [6] of this lens, and we choose MTF to be the standard. After assess circumspectly, the tolerance specification was being decided as below. In this conditions, 97.7% products can reach MTF>35%.

| Tolerance | Item | Specification |
|----------------------|---------------------------|---------------------------|
| Centered Tolerance | Test plate fit | 2 fringes |
| | Center thickness | 0.01 mm |
| | Material Index | Index: 0.0005 V: 0.5 % |
| | Irregularity | 1 fringe |
| Decentered Tolerance | Element Tilt | 1 ~ 2 arc min |
| | Element Wedge | 1 ~ 2 arc min |
| | Element Displacement/Roll | 0.01 mm |

Table 2 Tolerance specification

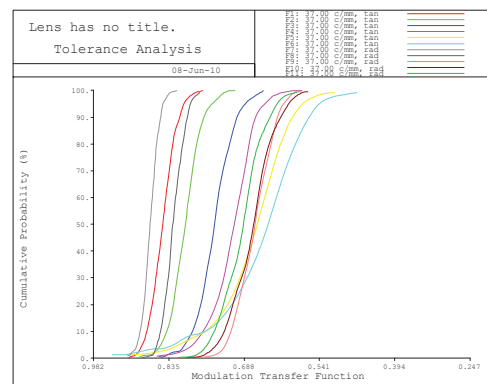


Fig. 8 MTF vs. probability

5. Optical system analysis

In this section, we combined Imaging system and lighting system together. Analyze the uniformity and light efficiency by using ASAP with 1.5 million rays. The following is the 3D layout of our system in ASAP. The total size of our design is **131mm × 94mm × 91mm**.

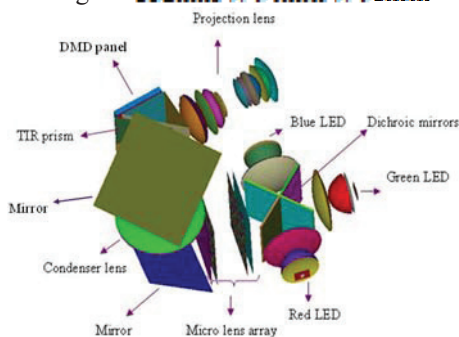


Fig. 9(a) The components 3D layout (a)

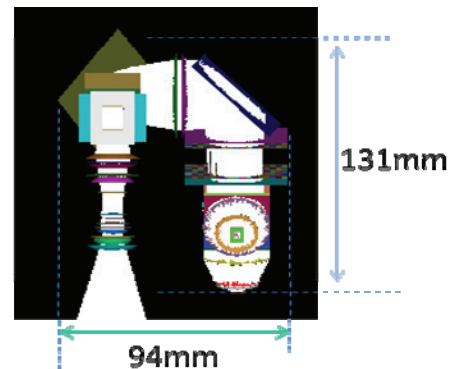


Fig. 9(b) The components 3D layout (b)

5.1 Uniformity analysis

About uniformity in this paper is using ANSI definition. After simulated by ASAP, the uniformity on DMD of Red light is 88.8%; Green light is 98.4% and Blue light is 98.3%. In addition, the Overfill which actually simulated is 22.9%. And about the uniformity on screen of Red light is 82.8%; Green light is 91.9% and Blue light is 87.9%.The energy distribution of each light source on screen is show as below.

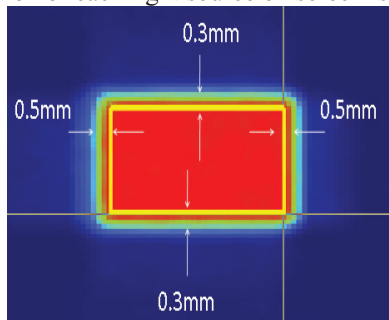


Fig. 10(a) Overfill on DMD

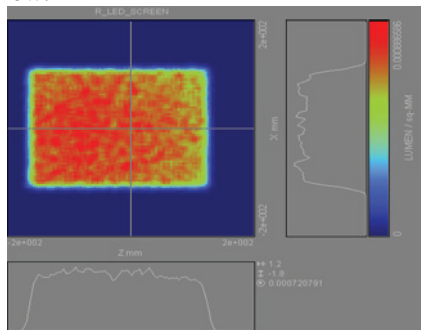


Fig. 10(b) The intensity distribution on screen of red light

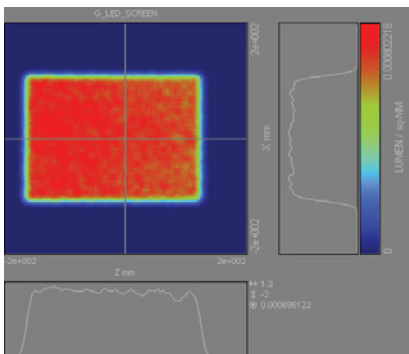


Fig. 10(c) The intensity distribution on screen of green light

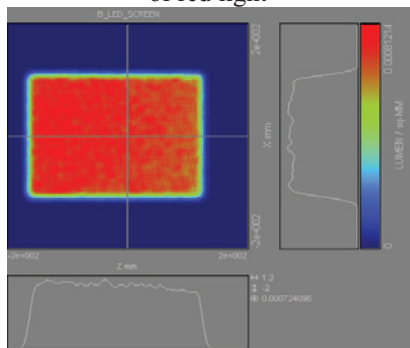


Fig. 10(d) The intensity distribution on screen of blue light

5.2 Light efficiency analysis

At first, we consider only the loss between components. In other words, it's in ideal cases. After simulated by ASAP, the loss rate of each component is show as Fig. 11. The ideal light efficiency on the screen is 44% about this design.

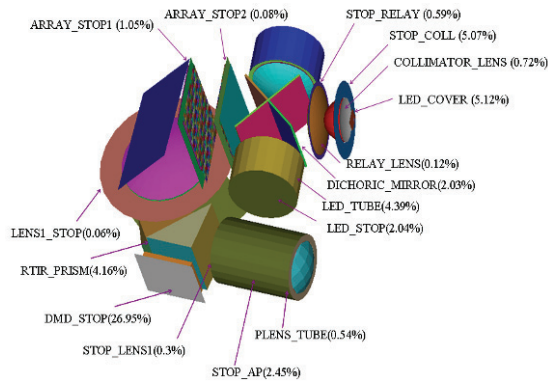


Fig. 11 The loss rate of each component in ideal case

| Lumen Budget | Description | PT54 LED | | |
|-------------------------|------------------------------|----------|--------|-------|
| | | R | G | B |
| LCD Spectrum | Dominant Wavelength | 625 | 525 | 462 |
| Lumilus R G B LED | PT54 LED Spec | 920.0 | 1725.0 | 320.0 |
| Duty cycle | Bright Sync | 25.0% | 50.0% | 25.0% |
| Lens 3 (E490R) | Transmittance | 97.0% | 97.0% | 97.0% |
| Lens 2 (BK7)_Relay lens | Transmittance | 98.5% | 98.5% | 98.5% |
| Dichroic mirror | Transmittance & Reflectivity | 90.0% | 90.0% | 90.0% |
| Fly Eye | Lens Array | 95.0% | 95.0% | 95.0% |
| Lens 1 (PMMA) | Transmittance | 97.0% | 97.0% | 97.0% |
| Mirror #1 | Reflectivity | 98.0% | 98.0% | 98.0% |
| RTIR-Prism | Transmittance | 90.0% | 90.0% | 90.0% |
| DMD Efficiency | DMD Size 0.55" 4:3 | 68.5% | 68.5% | 68.5% |
| Projection Lens | Transmittance | 95.0% | 95.0% | 95.0% |
| Mechanical tolerance | mechanical tolerance | 95.0% | 95.0% | 95.0% |
| Simulation Efficiency | From LED to Screen | 44.0% | 44.4% | 43.6% |
| Total Lumen on Screen | RGB Lumen value | 39.1 | 148.0 | 13.5 |
| Total Lumen | | 200.7 | | |

Table 3 The light efficiency of each components in real case

Then in the real case, we consider the duty cycle of each light source, transmittance, reflectance, and so on. The real light efficiency is showed in table 3. The total lumen on the screen is 200.7 lumen in real case. And the light efficiency in real case is about 16.3%.

6. Conclusion

This design uses single R, G, B LED light source with collimator lens and Dichroic filters to replace the mercury lamp (UHP). It reduce reflector, UVIR filter and color wheel. Using micro lens array replaces rod to increase uniformity and light efficiency. And the TIR prism was use to minimize the total track to 52mm. After considering the light efficiency, the projection size was designed in 20 inch. The light efficiency in real case is 16.3% on the screen and the uniformity on the screen is 87%. Finally the size of this pocket projector is **131mm × 94mm × 91mm**.

7. Acknowledgement

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